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USE OF ELECTROMAGNETIC COIL LAUNCHER TO INCREASE MUZZLE VELOCITY OF CONVENTIONAL CANNONS

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13. ABSTRACT (Maximum 200 words)

This paper describes the design and operation of an experimental hybrid cannon consisting of a 60-mm bore gas cannon using standard propellant and a traveling-wave induction accelerator. The projectile, consisting of an aluminum cylinder weighing 120 grams, is initially brought up to a speed of 600 m/s in the gas cannon. The pulsed-power stage is designed to accelerate the projectile further to a velocity of 700 m/s.

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INTRODUCTION

Projectile acceleration is most efficient in conventional chemical guns at low speeds. On the other hand, pulsed power guns are most efficient in the high-speed range. This makes for an ideal two-stage combination in which the pulsed-power stage is positioned at the muzzle end of the chemical gun.

CHEMICAL GUN

The gun is one of a series of thin-walled 60-mm research cannons designed specifically for vibration studies. Typically the transverse motion of the tube wall has been measured for a variety of boreshapes, created by planned manufacturing variation[1] and various support modes. It is of interest to determine the response of these barrels to axial loads directed toward the breech. Thus, forming the experimental cannon from a gas gun with an electromagnetic (EM) accelerator at the muzzle provides an opportunity to evaluate both the barrel response to axial loads created by an EM accelerator or any other source and the response of the EM device to the harsh environment at the muzzle end of a gas cannon. This includes transverse barrel whip, the through passage of a projectile that is already vibrating in multiple modes, and the passage of erosive, hot, high-pressure gas.

Chemical Gun Barrel

The barrel is an extra long construction with a high expansion ratio (*i.e.,* total volume divided by chamber volume). This usually provides a very high efficiency expansion and higher than usual velocity for a given ratio of charge mass to projectile mass. The barrel is 60-mm bore diameter and provides 3.5 meters of travel. Chamber volume is variable depending on the use of spacers, but in this case a volume of 150 cm^3 is provided behind the seated projectile. A quarter of the chamber is filled with 33 grams of propellant. This low charge imparts 600 m/s to the lightweight projectile, but more important, it provides a relatively (for cannon) low-pressure, low-erosive state to the propelling gas as it passes through the downbore EM device.

Since the primary objective of this hybrid construction is to produce axial forces, not to develop EM accelerators, the gas condition precludes a central problem in any hybrid accelerator; (*i.e.,* the fabrication of a bore liner that at once is transparent to rapidly varying magnetic fields while impervious to high-temperature erosive gases). For this research, the device only needs to be magnetically transparent and resistant to erosion for a few test rounds. Thus, a simple fiberglass/epoxy liner is used. To enhance survival of the liner, the barrel is supported to minimize bend and side thrusts between the projectile and liner.

Muzzle End Test Device

The muzzle end of the 60-mm cannon was modified by adding a thread and pilot zone (Figure 1) to accommodate a nut that is bore-sized on the inner surface and threaded on the outer surface. The nut's inner surface is recessed to receive the bore liner. The nut's outer surface supports a large diameter split aluminum casing. Both the casing and the bore liner extend forward 18 inches to join to the muzzle end nut, which continues the bore and provides muzzle

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end closure to the EM device. Thus, the annular volume enclosed axially between the end nuts and radially between the liner and casing defines a generalized test volume, allowing a wide variety of EM devices to be tested. Coax power cables are ported through the breech nut. Of the component joints, the threads joining the breech nut to the casing are the least robust and are sized for projectile-to-accelerator collision energy dissipation rate of 1.9MJ per meter. Thus, the 57KJ projectile of this test may be stopped in about a coil width without housing failure.

Electromagnetic Launch Section

The muzzle end EM launch section consists of a coaxial coilgun called the "linear induction launcher" (LIL).[2] It consists of a linear array of coils, energized by multiphase excitation. The currents in these coils generate a magnetic traveling-wave energy packet, which, in turn, induces currents in a conducting cylinder (sleeve) that houses the projectile. The interaction of these currents produces strong propulsion and centering forces.

Specifications and Constraints

The electric stage of the hybrid gun is required to increase the velocity of the projectile from 600 to 700 m/s, subject to the following constraints:

Power supply: Only 12 capacitors, 22 kV, 51 µF and three ignitron switches were available
Coilgun Barrel: 60-mm inner diameter, 264-mm long, mounted at the muzzle end of the gun
Projectile: A hollow aluminum cylinder weighing 120 grams

The dynamic resistance of the capacitors and switches has not yet been measured. Since the total resistance determines the rate of decay of the current in the barrel coils, muzzle velocity cannot be predicted with high accuracy. In the future, consideration will be given to the use of a flywheel motor/generator set in place of the capacitor bank to reduce the bulk and weight of the power supply.

Design Procedure

With three-phase energization, the pole pitch is uniquely determined once the number of coils has been prescribed. The supply frequency is also uniquely determined based on assumptions of the values of the muzzle velocity and for the slip of the projectile behind the EM wave traveling down the barrel. From the value of the capacitance and circuit resistance, resonance with the barrel coils determines the values of their inductances, and therefore, the number of turns. In this case, the unknown dynamic resistance of the capacitor and switches constitutes the dominant part of the total circuit resistance and, hence, is a source of uncertainty. Also, the number of coils, 12, represents four pole pitches (4τ) and allows some flexibility with their parallel or series connection. The assumed enhanced muzzle velocity, (i.e., 700 m/s) determines the final kinetic energy of the projectile and, hence, the average EM force acting on it. Using formulas previously derived and validated [3] for a steady-state condition, it becomes possible to predict the coil currents and voltages.

Design Specifications

The procedure outlined above leads to the following dimensions and data.

The coils are double-pancake type, each with a total of 6 turns (3 turns in each half-coil); 60-mm inner diameter, 6-mm height, 20-mm width; 60 kA peak current and 7.5 kV peak voltage. The connections for phase A are shown in Figure 2.

The series/parallel connection is dictated by the value of available capacitors. A finite element method (FEM) is used to evaluate mechanical forces. Each coil is subjected to a peak longitudinal stress of 22 MPa and a peak radial stress of 44 MPa.

The coils are constructed with NELB 15/18 litz wire. For connection to the pulsed power supply, the coils are fitted with tabs containing three surfaces on both terminals for crimp connections. These tabs permit three RG217 #10 coax cables to supply each branch of the three-phase arrangement for a total of 18 total wires feeding 6 sets of coils. Two different coil configurations were constructed: six wound left and six wound right. This permits the center conductor of the coax to feed through the tabs of the first coil and connect to the second coil in the set to provide continuous shielding.

The center of the length of litz wire for the coil is laid in the center of three G10 disks and wound left or right to complete the coil shown above (Figure 3). The litz wire is braided with fiberglass for mechanical strength and voltage standoff. The coils are designed for 1500V turn to turn. The coils are filled under vacuum with epoxy and, after primary cure, overwrapped with 1 cm of fiberglass, then final cured. One of each left and right wound coil was fabricated for a 2-coil single-phase test.

Initial circuit modeling showed that 8KJ of KE can be added to a projectile. A projectile entrance velocity into the LIL of 600 m/s was selected. Choosing a velocity increment of 100 m/s, based on the limited available energy, meant that the projectile mass should be about 120 g. This mass provides a 60-mm diameter aluminum cylindrical projectile with 2 calibers of wheel base and a wall thickness on the order of a few millimeters. Impulse to the barrel is 12 Nsec at an average force of 30,000 N.

The projectile (Figures 4a and 4b) is designed for the peak acceleration required to meet the velocity goal. This, in turn, is based on the peak gas pressure. The base is a separable pusher plate. The cylindrical sleeve is the singular EM-driven entity with 120 g mass budget allocated to it. Interior ballistic calculations initially showed that a fully burned charge produces 117 MPa in the 150 cm^3 chamber and propels a combined mass of 234.5 g to 600 m/s. The 114.5 g allocated to the pusher plate corresponds to a 15-mm thickness. Finite element analysis indicates pusher plate face tension at the 103 MPa level. Cylinder wall thickness is 1.3 mm at the leading edge. Rearward, the wall thickens exponentially to 3.83 mm to hold the compressive contact stress at the cylinder/pusher plate junction to 234 MPa. Recent modeling shows a peak magnetic external pressure of 43 MPa is expected. The skin depth-based wall thickness may be marginal to survive this load. However, recent charge establishment firings with slug (weight simulating) rounds and available propellant showed that 600 m/s could be attained with a peak gas pressure

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of only 34 MPa. Thus, the forward wall may be thickened to resist radial load, while a thinner base will not exceed the 234 MPa base contact stress limit.

PREDICTED PERFORMANCE

To predict the LIL section performance, a previously developed mesh-matrix code [4] is used. Each drive coil is represented as a lumped R-L-C circuit. The projectile is assumed to be segmented into 20 coaxial rings, and each is represented by an R-L lumped circuit. The mutual inductances among all of the drive and projectile coils are recalculated during each iteration (i.e., each incremental movement of the projectile). The code provides results for the voltage and current of each coil of each phase, the position of the projectile, temperature rise in both the drive and projectile coils, projectile velocity, acceleration, and mechanical forces acting on the projectile. It also allows the system parameters to be optimized.

By interconnecting the capacitors to form a bank of 204 μF per phase, the required input frequency, f, becomes 6,333 Hz. The synchronous velocity of the traveling magnetic wave is V_s $= 2\tau \cdot f = 836$ m/s, where τ=pole pitch = 0.066m. The first phase of the LIL is triggered when the relative position of the rear of the incoming aluminum projectile with respect to the entry plane of the coilgun section is -11 mm. The negative sign indicates the 13.2-cm-long projectile is almost completely inside the coilgun section. The other two phases are self-triggered 60° later, 60° apart. For an initial voltage of 13.5 kV per capacitor per phase, and assuming $r = 0.01\Omega$ for the per phase combined resistance of the capacitor bank, ignitron switch and circuit cable wiring, the computer code predicts the results described in Figures 5, 6, and 7.

Figure 5 shows the three-phase drive-circuit currents. The amplitude difference between the current in the first pole-pair (i_{A1} in Figure 2) and the second pole-pair (i_{A2} in Figure 2) is caused by the effect of the mutual inductances between the projectile and the corresponding section of the barrel.

The force curve (Figure 6) exhibits strong temporal fluctuations. The net effect of this force produces the velocity profile shown in Figure 7. The sleeve is accelerated from an initial speed of 600 m/s to a final speed of 700 m/s in a transit time of 0.44 ms, corresponding to an average acceleration of 23,000 gee's. Our analysis suggests that the projectile currents give rise to two magnetic waves. The first is "frozen" into the projectile; (i.e., it moves forward at rest with respect to the projectile, at its speed v<v_s). Hence this projectile field slips slowly backward with respect to the synchronously moving barrel field, causing strong force fluctuations. The second magnetic wave, generated when the leading edge of the sleeve abruptly hits the barrel field when the first phase is switched on, travels back toward the breech at speed v. This end effect [5,6] causes the negative force at the beginning of Figure 6. After the traveling wave has been established, the force is consistently positive.

A rotating machine, such as a synchronous generator (flywheel motor/generator set), may be used to replace the capacitor bank. This will reduce the volume and weight of the pulsed power source and permit the LIL section to be energized before the chemical gun fires. Through this means, it will accelerate the projectile as soon as it arrives in the LIL section without requiring a special synchronizing switch.

PRELIMINARY TESTING OF THE GAS GUN

A series of preliminary test shots of the gas gun was performed. These shots have established the propellant charge mass to achieve 600 m/s for various projectile masses, (*e.g.*, 33.5 g of propellant for 234.5 g projectile mass, and 46.5 g for a 412 g projectile mass). Pressure vs. time has been recorded and shows that a smooth propellant burn is achieved. Post-shot inspection shows complete burn. Doppler radar was used to measure velocity, a chamber pressure piezo gage was installed, and witness cards were set up 8, 12, and 60 feet from the muzzle. General TV coverage of the range event was operating.

Upon firing, velocity rose to 574 m/s. The velocity trajectory is discerned from the Doppler radar data via time-frequency analysis.[7] This provides measurement of armature/projectile velocities during both the interior and exterior ballistic launch cycle. It is anticipated that armature separation from the pusher-plate will be readily discernible. Piezo data was lost. Witness cards showed the circularity of the cylinder was retained, and no buckling occurred. Recovery of large pieces of the cylinder showed unmarked leading edges, indicating very smooth entry into the fiberglass bore liner and the following muzzle nut. The bore liner showed no lifting or fiber separation at interface edges. No effects of heat transfer and erosion were observable within the bore liner. In particular, initial pits or voids between fibers caused by poor resin fill did not grow or melt despite increased heat transfer at pit edges. This indicates that the liner can withstand higher pressure and velocity firings. The bore liner was installed with two prototype coils and size/mass simulators for the other coils to assess its ability to withstand lateral forces associated with lateral acceleration of the coil stack due to barrel whip. Data for vertical acceleration at the rear nut was lost. Data for horizontal and vertical eddy probe measurement of displacement at the accelerator casing was also lost.

A first check of the projectile locator system was performed. The system is based on the conductive projectile changing the capacitance of two plates posed near the bore at entry to the LIL. A measuring circuit resolves projectile position to less than a millimeter statically. The firing test confirmed function at 600 m/s but was not set up to measure accuracy. The difference between statically measured position and firing measured position was not determined. Figure 8 is a composite graph of breech pressure with radar output and the projectile locator system output overlaid. The locator output is the pulse before the large signal change on the radar signal. There was a misalignment of the radar that attenuated the signal. The wave in the radar signal between 5 ms and 10 ms is due to the recoil velocity of the gun. One full cycle is 1 cm of travel; the gun recoils 8.5 mm before the 412 g projectile exits at 600 m/s.

The first test for the hybrid system will consist of a two-coil powered test that uses the projectile locator system to trigger one phase of the pulse power supply. The coils will be spaced the same as in the 12-coil arrangement. The expected force from the two-coil drive is 25kN.[8] The expected velocity gain is small due to the low voltage, 5 kV, applied and the large mass of the projectile.

The full 12-coil arrangement will be assembled and a number of electrical and mechanical tests will be performed prior to hybrid operation.

SUMMARY

The paper has presented a hybrid concept: a chemical/EM gun in which the EM coil part is attached as an extension to the muzzle end of the conventional gun. Design specifications, initial tests, and computer code predictions are described. Constraints imposed on the power supply and design are expected to adversely affect the performance of the present hybrid gun. Nevertheless, much will be learned about the potential of this new concept. Construction of the system is virtually complete. It is expected that the first test firing of the hybrid gun will be made in 1997. The actual experimental results will provide a learning tool for scaling up and optimization. Since the LIL can operate using an alternating-current-energization system, it is possible to use a flywheel motor/generator set, instead of the capacitor bank. It is anticipated that this will greatly reduce the volume and weight of the pulsed power supply.

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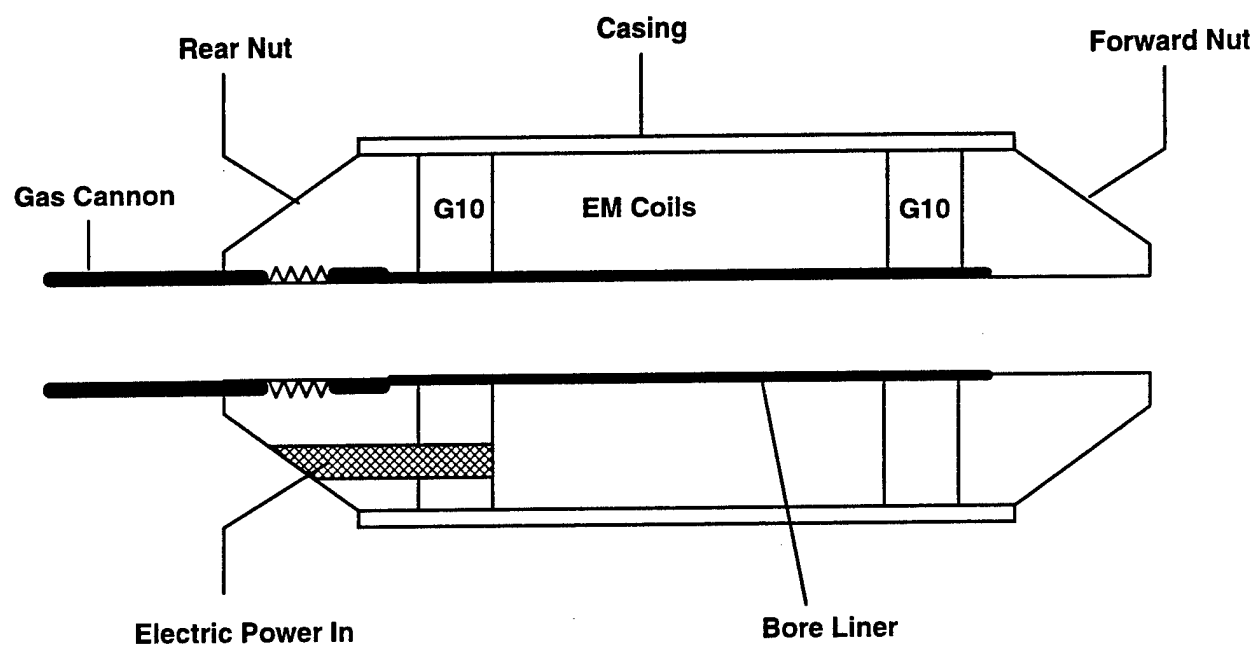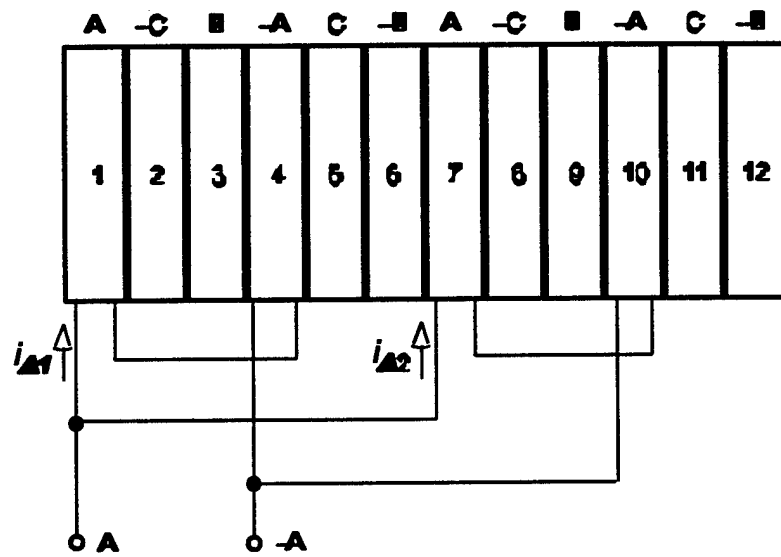
Figure 1. Muzzle end EM device

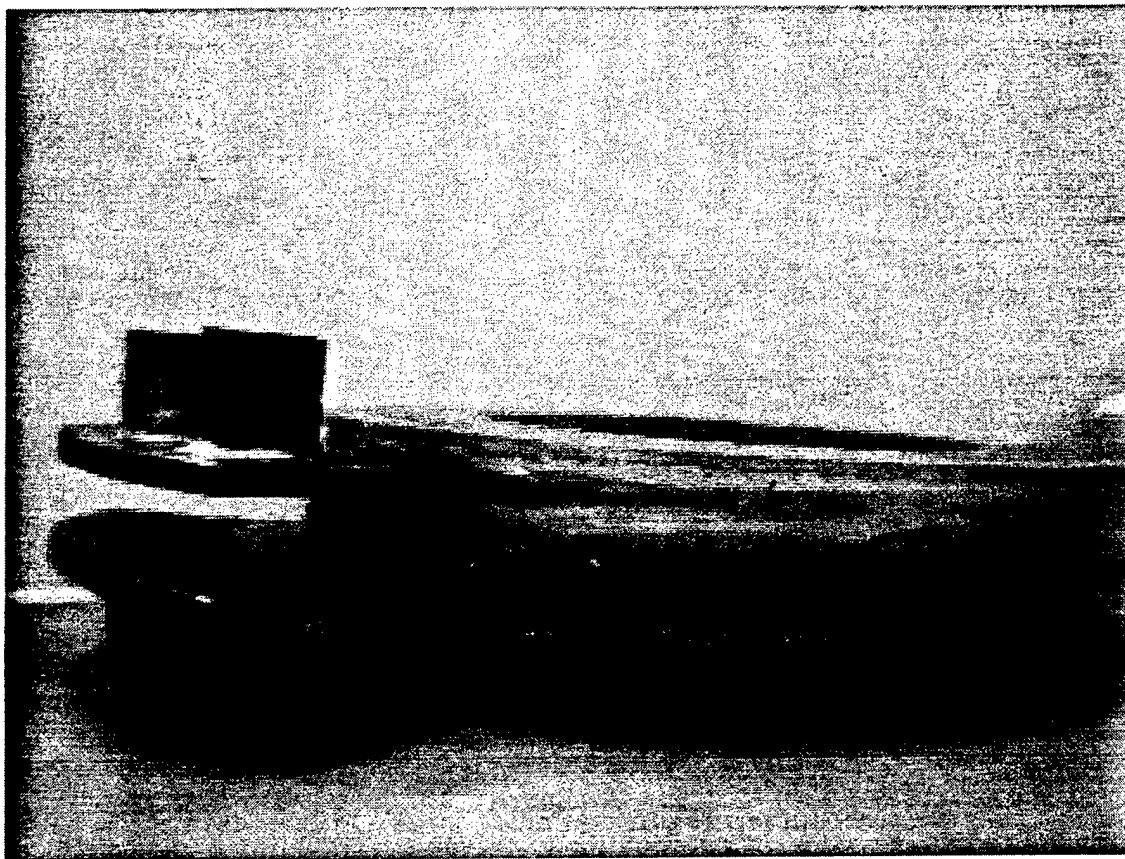**Figure 2. Terminal connection of one phase of the LIL section**

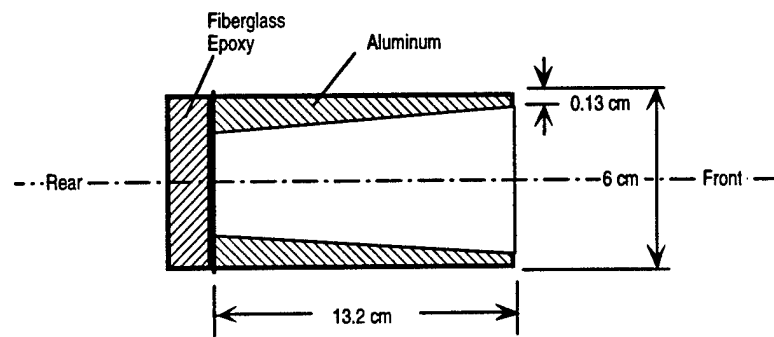**Figure 3. Photo of pancake coil showing feed-through terminals for coax cables**

Fiberglass
Epoxy Aluminum

0.13 cm

Rear 6 cm Front

13.2 cm

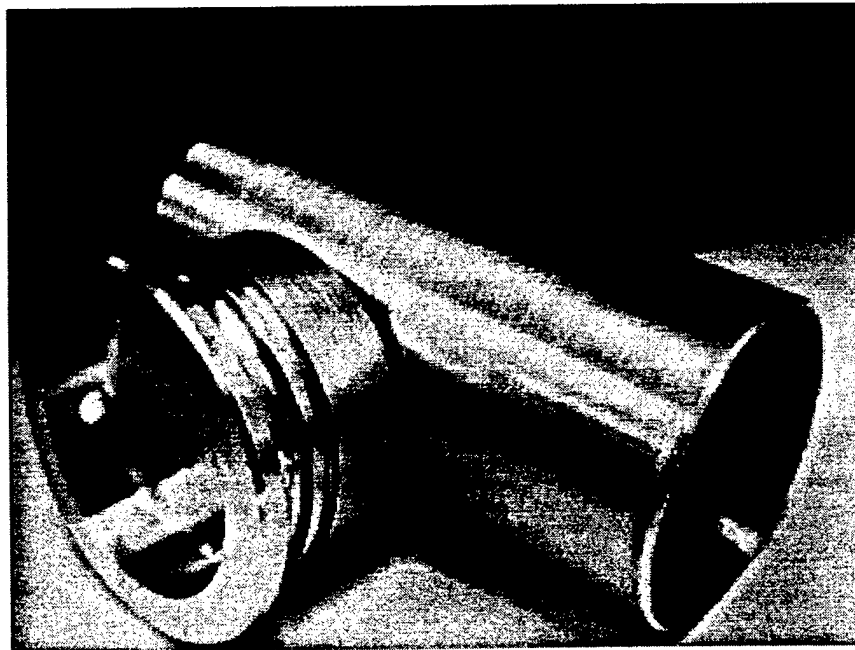**Figure 4a. Cross-section of projectile assembly**

Figure 4b. Photo of projectile with Al pusher plate
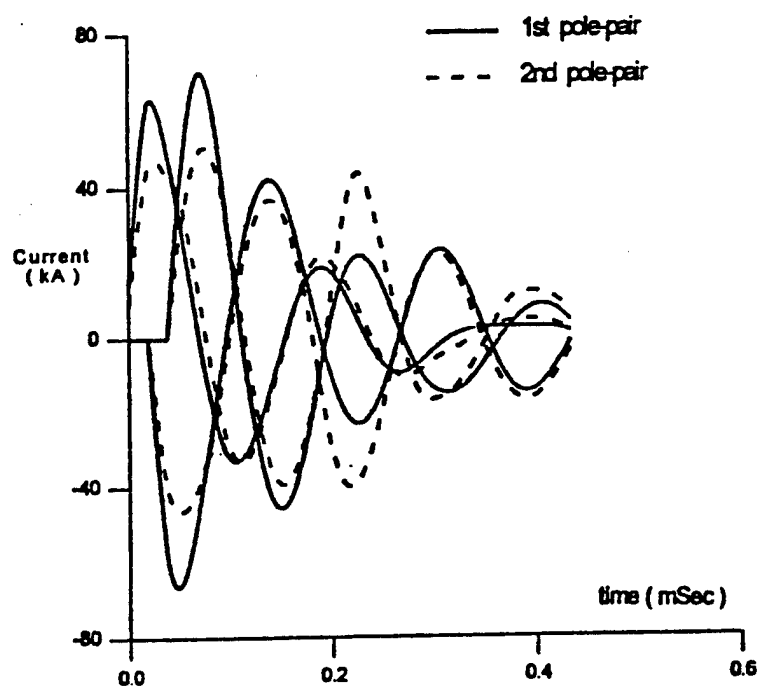
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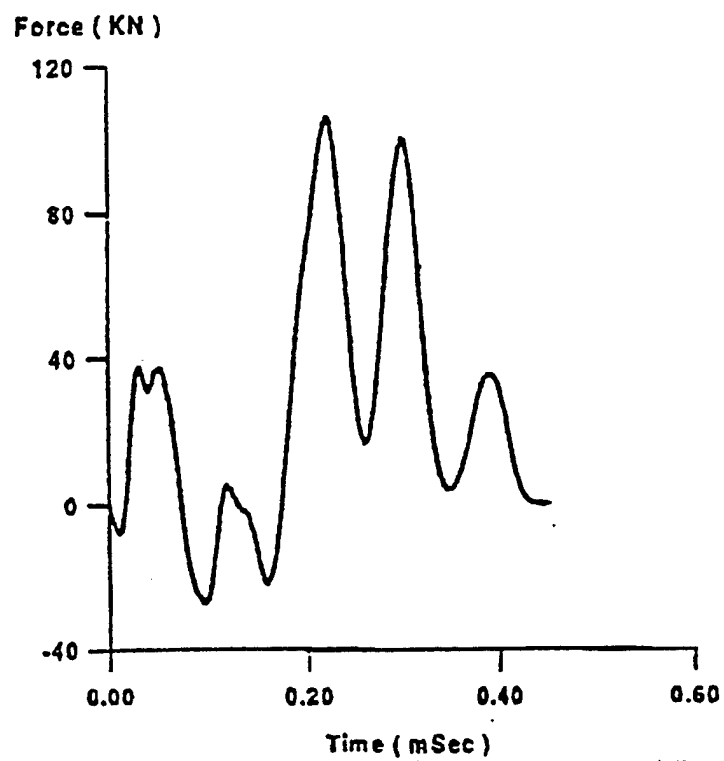**Figure 5. Currents in the two parallel parts of the LIL**
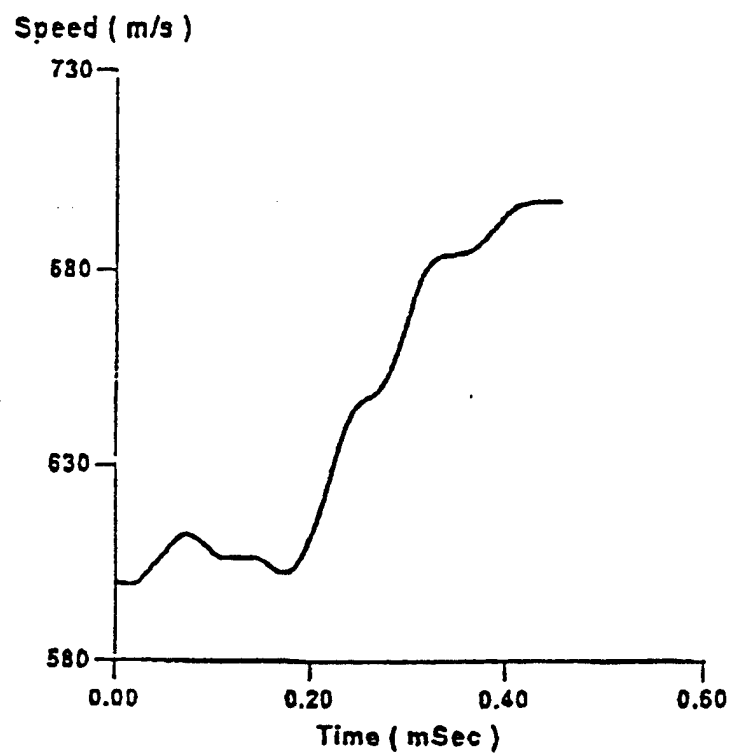
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Figure 6. Longitudinal force vs. time

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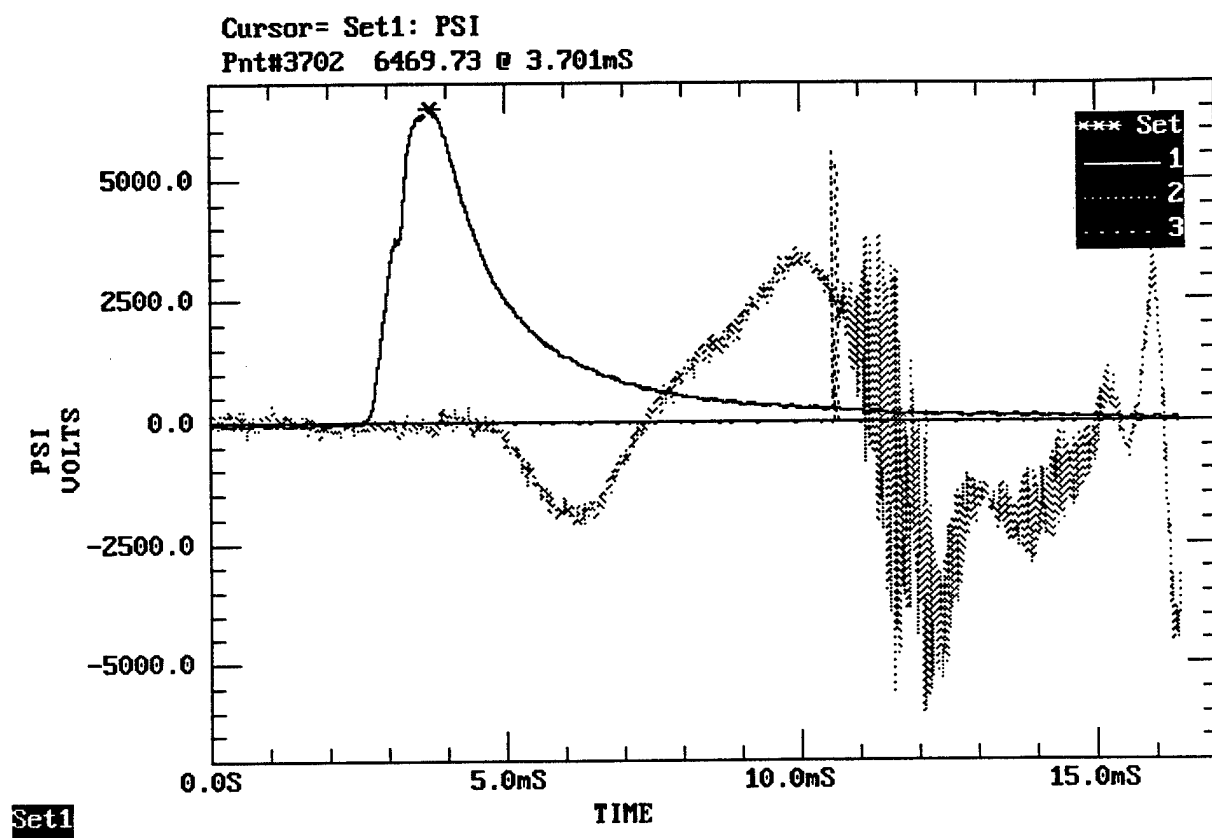**Figure 7. Projectile velocity vs. time**

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Figure 8. Graph showing (1) breech pressure, (2) radar output, and (3) output of projectile locator system

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